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TECHNICAL NOTE

No. 1227

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EXPLORATORY INVESTIGATION OF LAMINAR BOUNDARY-LAYER
OSCILLATIONS ON A ROTATING DISK

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SUMMARY

Sinusoidal waves excited by random disturbances have been observed in the laminar boundary layer of a rotating disk at Reynolds numbers in a narrow range below the Reynolds number of transition. Their frequency was found to be approximately a constant times the angular velocity of the disk. The velocity of the waves at a radius of 11 inches was determined and found to be 0.2 linear velocity of the disk in a downstream direction, making an angle of approximately 14° with the outward-drawn radius vector.

INTRODUCTION

A thorough study of boundary-layer oscillations on a flat plate has been made at the National Bureau of Standards (reference 1), and good agreement with the theory developed by Schlichting (references 2 and 3) for two-dimensional flow was obtained. Knowledge of these flat-plate experiments became available while measurements of drag on rotating disks were being made at the Langley Memorial Aeronautical Laboratory (reference 4), and it was decided to determine whether or not fluctuations in the boundary layer on a rotating disk could be observed. Waves were found with no excitation other than the random disturbances present in the room, but no extensive study of these waves has been undertaken. Mention was made in reference 4 of some of the results. The purpose of this paper is to describe the equipment used and to give the results of the exploratory tests made.

SYMBOLS

N	rotational speed of disk, revolutions per minute
x	radius at which hot wire is located
z	distance from disk measured along a line parallel to axis of rotation
U	velocity of fluid parallel to disk surface measured relative to fixed coordinates
V_w	wave velocity relative to fixed coordinates
ν	kinematic viscosity
Ω	wave frequency, cycles per second
ω	disk angular velocity, radians per second
δ^*	boundary-layer displacement thickness $\left(\int_0^\infty \frac{U}{\omega x} dz \text{ or } 1.37 \sqrt{\frac{\nu}{\omega}} \right)$
R_x	Reynolds number based on radius to hot wire $\left(\frac{\omega x^2}{\nu} \right)$
R_{δ^*}	Reynolds number based on boundary-layer displacement thickness $\left(R_{\delta^*} = \frac{\omega x}{\nu} \delta^* = 1.37 \sqrt{R_x} \right)$

EQUIPMENT

Measurements of oscillations were made by placing a hot wire in the boundary layer of the rotating disk. The hot wire formed one arm of a Wheatstone bridge, and unbalance of the bridge caused by fluctuations in the hot-wire resistance was recorded on an oscillograph. A schematic diagram of the circuit used is given in figure 1. An amplifier, not shown, was connected between the bridge output and the oscillograph. The hot wire used was 0.00025-inch-diameter platinum wire approximately 0.15 inch in length and was obtained by etching the silver from Wollaston wire. The ends of the wire were soldered to the points of two rigidly mounted sewing needles.

The hot wire was kept parallel to and about 0.03 inch from the disk face. When measurements were made, current through the bridge was adjusted to a value such that the temperature of the wire was just below the temperature which would give the wire a dull glow. The resistance of the wire when hot was found to be approximately twice the resistance when cold.

In practice, the following procedure was used in making measurements. The resistance of the cold wire was measured by balancing the bridge with the galvanometer in the circuit and with low bridge current. This resistance was approximately 15 ohms. The variable resistance in the bridge was then increased to double the cold-wire balance value, and the current in the bridge circuit was increased until the bridge again balanced. The switch was then thrown to the oscillograph circuit, the disk was rotated, and records were taken. The data given in this paper were all taken on a polished steel disk having a radius of 12 inches and a thickness of 5/16 inch. In order to exclude the possibility of excitation of boundary-layer oscillations by disk or motor vibrations, tests were run on a number of other disks of different radii and thicknesses and on another motor with results consistent with those reported herein. Also, disks with sharp tapered edges and rounded edges were used to show that the unrounded edge of the 12-inch-radius disk had no effect on results.

In tests to determine the magnitude and direction of wave velocity two hot wires were used instead of one. The two parallel hot wires were mounted 0.25 inch apart on a head that could be rotated about an axis perpendicular to the face of the disk through the center of one of the wires which was at a radius of 11 inches. The wires were parallel to and approximately 0.025 inch from the face of the disk. A photograph of the apparatus used for the velocity measurements is shown as figure 2. Figure 3 shows the two-wire head near the face of the disk.

The method used in mounting the wires was conventional. A piece of Wollaston wire approximately twice the length needed was fastened to a strip of plastic material with wax. The wire was then dipped into a warm solution of 5 parts nitric acid to 4 parts water until the silver coating was removed from the platinum. The silver turned white in the solution and could be examined under a glass. The needle points were tinned with solder composed of 50 percent tin and 50 percent lead. The wire was laid on one of the needle points and a hot soldering iron was touched to the needle. The wire was then stretched across the other needle point and soldered.

METHOD AND RESULTS

Oscillograms were made with the hot wire in the boundary layer at radii varying from 5 to 11 inches on the polished steel disk having a radius of 12 inches. The hot wire was oriented to give maximum sensitivity. The disk was rotated at a number of angular velocities in a room without drafts.

Figure 4 is a series of records taken with the disk rotating at various speeds keeping the hot wire at a 9-inch radius. Change of the boundary-layer flow from smooth laminar to sinusoidally oscillating to turbulent is shown. The Reynolds numbers based on radius to hot wire R_x appearing in the figure are given by

$$R_x = \frac{\omega x^2}{U}$$

The uniform wave at the top of each record is a 300-cycle-per-second timing wave.

Change in frequency with radius, keeping the Reynolds number almost constant, is illustrated in figure 5. The number of wave cycles per disk revolution was observed to be almost constant, varying only a few cycles per revolution from the mean value of 32.

Frequencies obtained at various angular velocities and radii are tabulated in table I. The Reynolds numbers R_{δ^*} given therein are based on the boundary-layer displacement thickness. By graphical integration of curves obtained from reference 5 for resultant velocities parallel to the surface of the disk, the boundary-layer displacement thickness was found to be

$$\delta^* = \int_0^{\infty} \frac{U}{\omega x} dz = 1.37 \sqrt{\frac{U}{\omega}}$$

and the Reynolds number based on δ^* was found to be

$$R_{\delta^*} = \frac{\omega x}{U} \delta^* = 1.37 x \sqrt{\frac{\omega}{U}} = 1.37 \sqrt{R_x}$$

Experience with rotating disks has shown that transition to turbulent flow on a disk occurs at $R_{\delta*} = 765$ approximately. This number was obtained by using the equation for $R_{\delta*}$ and substituting for R_x the value 310,000 given in reference 4 for the Reynolds number at which the initial rise in disk moment coefficient due to turbulence was observed. An oscillogram of the oscillations in the boundary layer of the disk at this Reynolds number is shown in figure 4(d).

A comparison of Reynolds numbers in table I of this paper with the Reynolds numbers on a boundary-layer-velocity survey graph in reference 4 shows that the data given herein were taken at Reynolds numbers just below the Reynolds number at which the boundary layer begins to thicken rapidly in the transition region. The validity of a comparison of the three-dimensional flow on a rotating disk with two-dimensional flow on a flat plate will be questionable until a theoretical analysis of the disk case is made. If an assumption of comparability is made, however, the conclusion may be drawn that the flow on a disk is more unstable than the flow on a flat plate, since the oscillations and transition on the disk occur at Reynolds numbers considerably lower than the corresponding Reynolds numbers for a flat plate. In reference 1 waves on a flat plate due to random excitation were found at boundary-layer Reynolds numbers from about 1800 to 3200 as compared with 620 to about 760 on a rotating disk. It should be pointed out that frequencies on a flat plate are measured relative to a point at rest on the plate. In the disk measurements the hot wire was not rotated with the disk, and therefore the frequencies measured in the two cases are not directly comparable.

A set of measurements was made to determine the magnitude and direction of wave velocity relative to fixed coordinates at a radius of 11 inches and a disk angular velocity of 500 rpm. The velocity of waves can be determined by measuring the wave frequency and the phase lag between two points in a line coinciding with the direction of wave propagation. The wave length is simply the distance between the points multiplied by 2π and divided by the phase lag in radians. The velocity is frequency times wave length. In order to determine the velocity, oscillograph records were made with the two-wire head at a number of angular settings. Phase differences between the two traces on the oscillograms were measured and plotted as a function of the angular position of the head. The points fell approximately on a sine curve. When the phase difference was zero, a wave crest was reaching both wires at the same time. When the phase difference was a maximum, a line joining the centers of the two wires coincided with a line in the direction of wave propagation. From the angular

orientation of the head at maximum phase lag the direction of wave travel was obtained. The magnitude of the maximum phase lag gave the magnitude of the wave velocity. For the case studied the velocity was found to be downstream, making an angle of approximately 14° with an outward-drawn radius vector and having a magnitude of 0.2 linear velocity of the disk at the same radius. The orientation and magnitude of this wave velocity V_w are shown in figure 6.

In order to determine whether or not the direction of wave travel changed with distance from the rotating disk, the two hot-wire bridge outputs were connected to a cathode-ray oscillograph and the hot-wire head turned until the two signals were in phase. The head was then slowly moved away from the disk surface and signals were observed to remain in phase, indicating that the wave propagation direction was unchanged with distance from the disk.

CONCLUDING REMARKS

An exploratory study has been made of laminar-boundary-layer oscillations on a rotating disk. With excitation by random disturbances sinusoidal waves were observed in a narrow range of Reynolds numbers just below the transition Reynolds number. The wave frequency, measured in a stationary coordinate system, was found to be approximately a constant times the angular velocity. At an 11-inch radius and a disk rotational velocity of 500 rpm the wave velocity relative to fixed coordinates was found to be 0.2 linear velocity of the disk and was in a downstream direction, making an angle of approximately 14° with an outward-drawn radius vector.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., December 30, 1946

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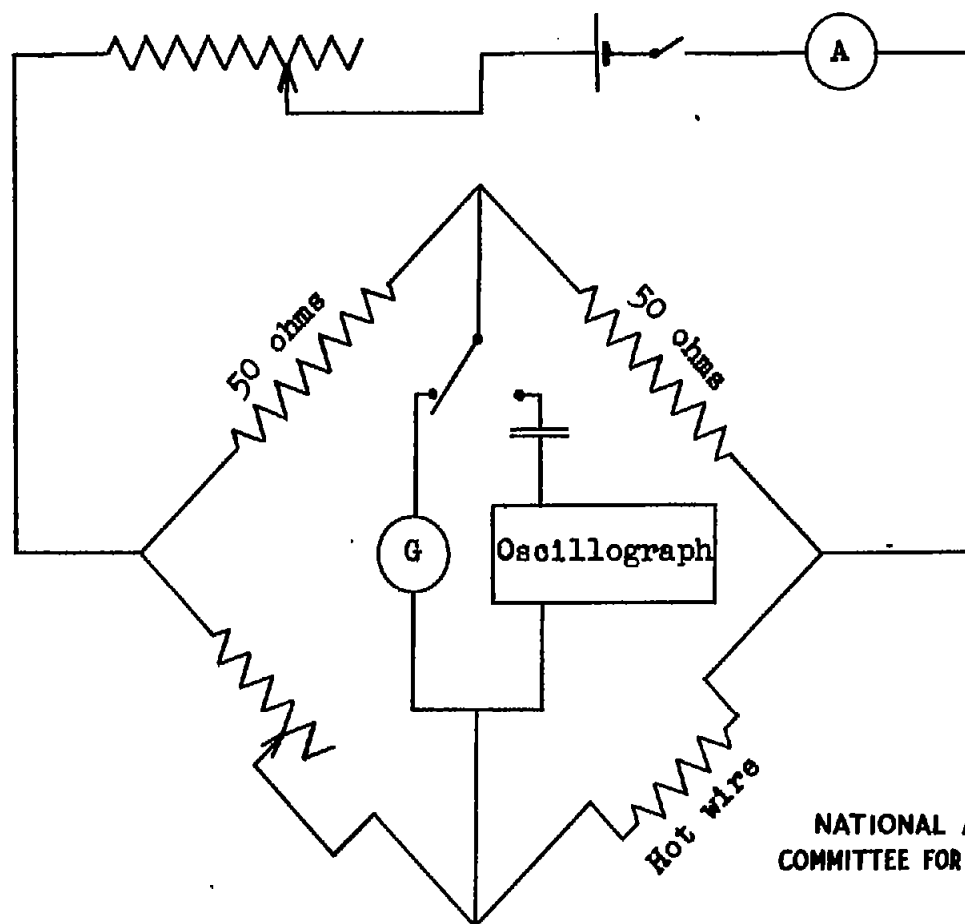
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TABLE I

WAVE FREQUENCIES OBTAINED AT VARIOUS ANGULAR
VELOCITIES AND RADII

Radial position of hot wire, x (in.)	Rotational speed of disk, N (rpm)	Wave frequency relative to fixed coordinates, Ω (cps)	Reynolds number based on boundary - layer displacement thickness, R_{δ^*}
5.00	2120	1090	658
5.00	1920	930	626
7.00	1100	579	663
7.25	980	464	650
7.33	1100	492	695
9.00	660	338	661
9.00	720	487	690
9.00	580	312	620
11.00	520	270	718
11.00	450	268	666
11.00	420	240	645
11.00	420	238	645
11.00	420	230	645

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Figure 1.- Diagram of hot-wire circuit. A, ammeter; G, galvanometer.

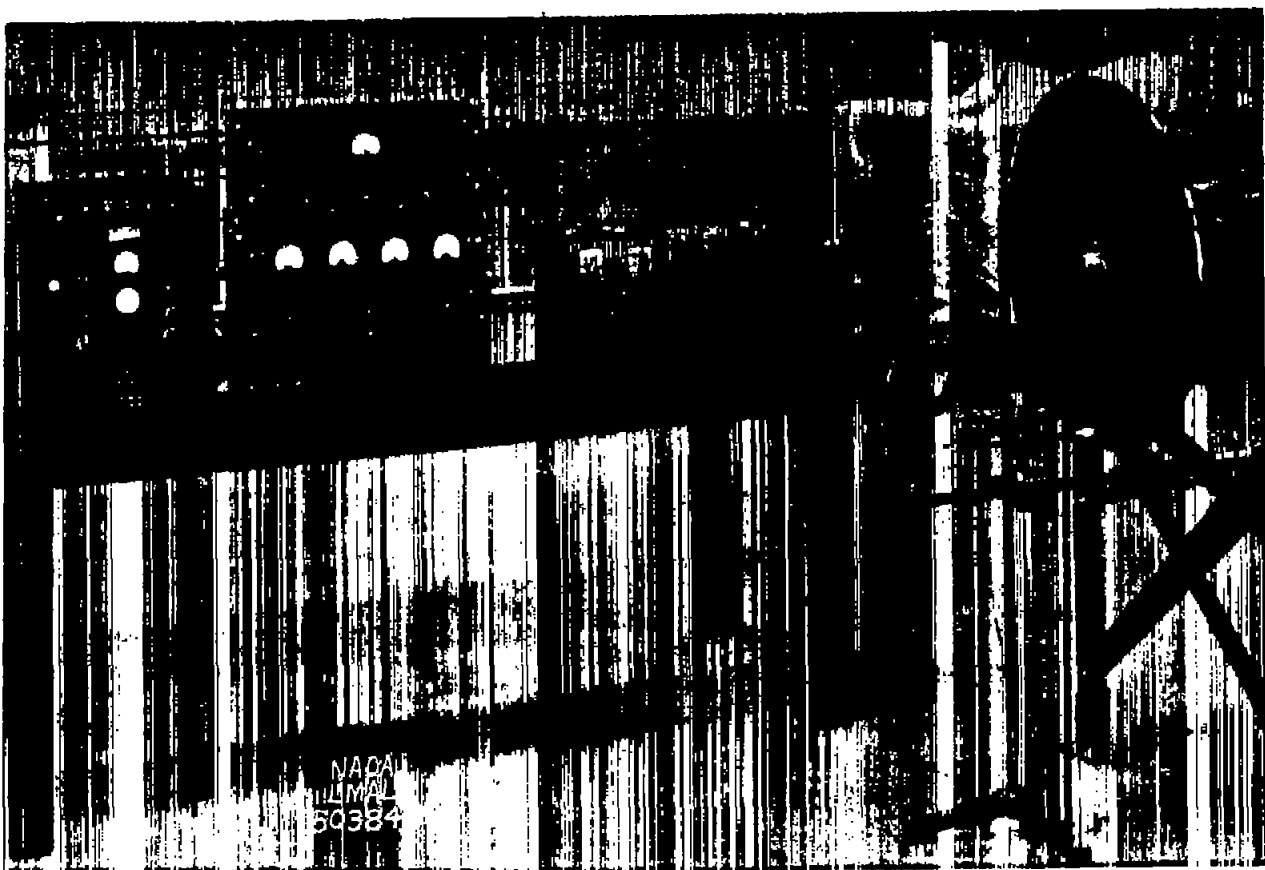


Figure 2.- Apparatus used in wave-velocity measurements.

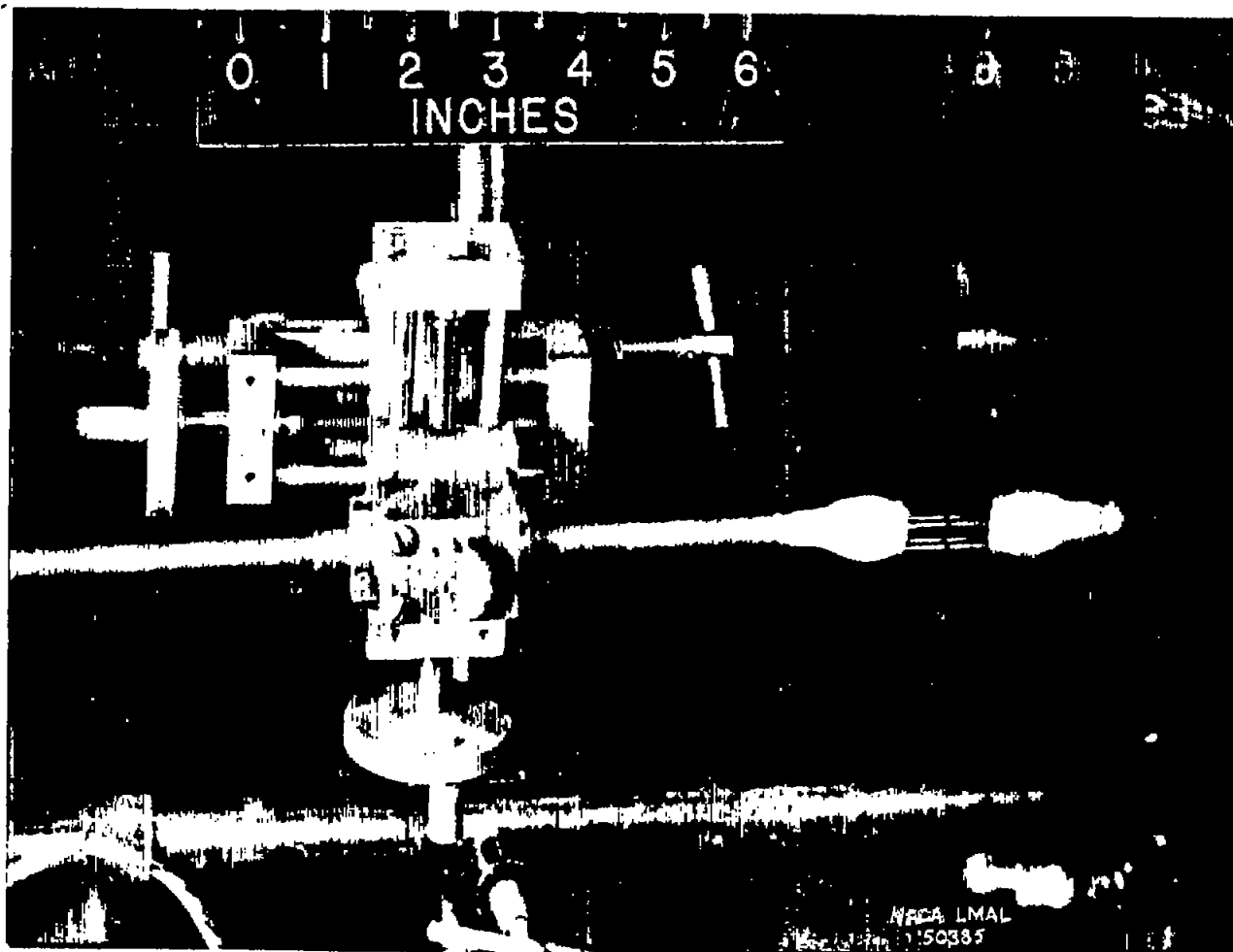
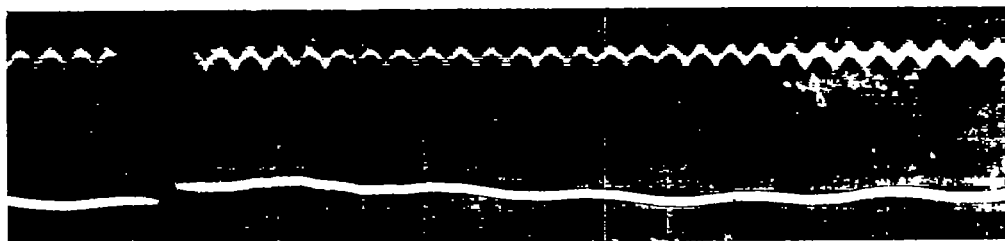


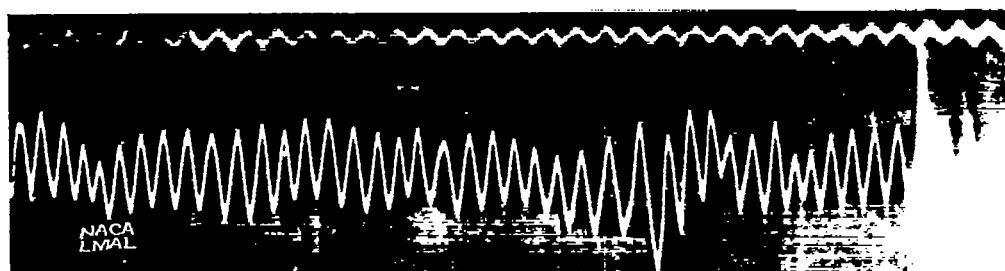
Figure 3.- Two-wire head mounted near the disk.



(a) $R_x = 159,000$; $N = 430$ rpm.

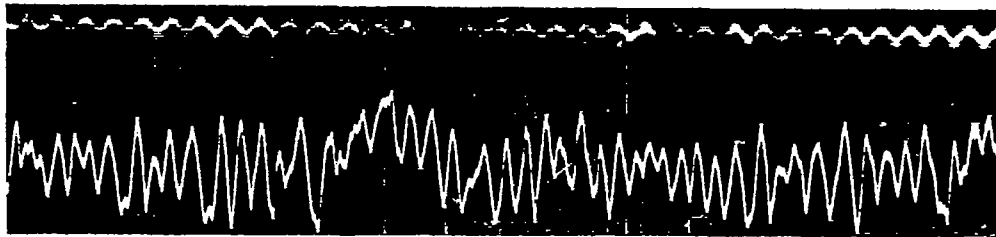


(b) $R_x = 214,000$; $N = 580$ rpm.

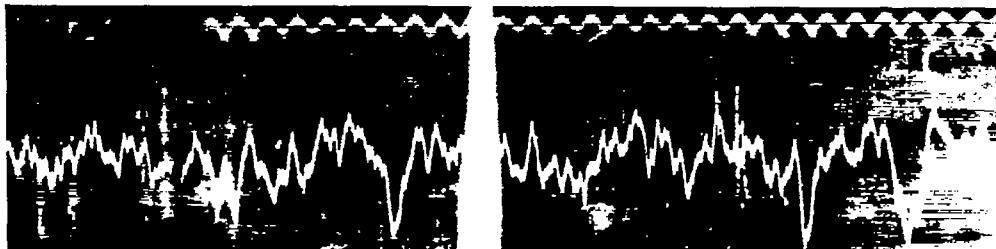


(c) $R_x = 265,000$; $N = 720$ rpm.

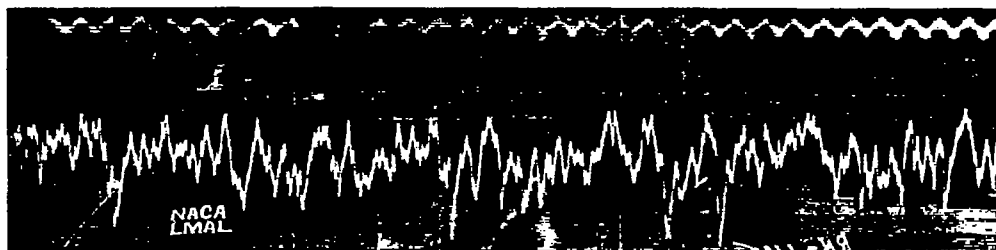
Figure 4.- Typical oscillograms showing the oscillations in the boundary layer of the rotating disk at the 9-inch radius.



(d) $R_x = 310,000$; $N = 840$ rpm.

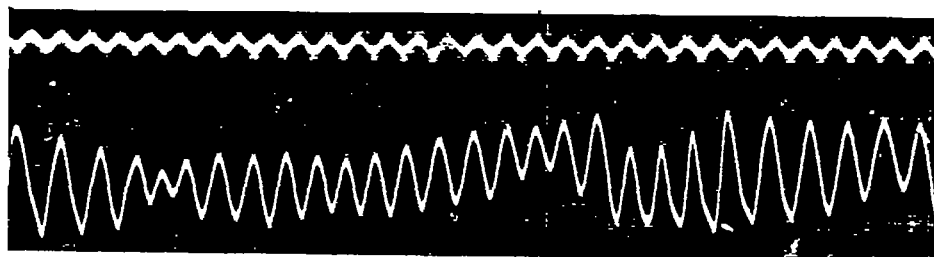


(e) $R_x = 384,000$; $N = 1040$ rpm.

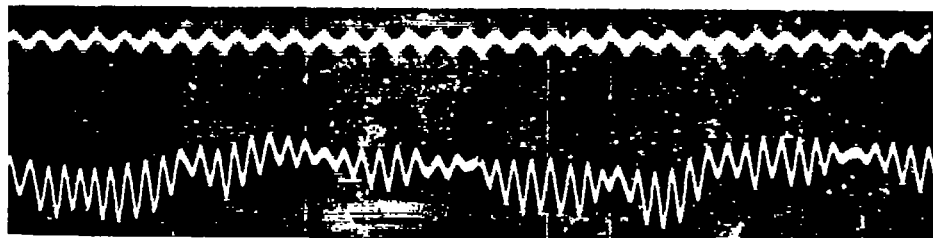


(f) $R_x = 1,105,000$; $N = 3000$ rpm.

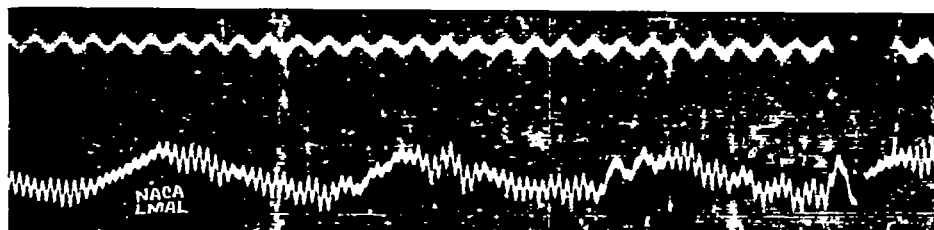
Figure 4.- Concluded.



(a) $R_x = 237,000$; $N = 450$ rpm; $x = 11.0$ inches;
 $\Omega = 268$ cycles per second.



(b) $R_x = 257,000$; $N = 1100$ rpm; $x = 7.33$ inches;
 $\Omega = 492$ cycles per second.



(c) $R_x = 231,000$; $N = 2120$ rpm; $x = 5.0$ inches;
 $\Omega = 1090$ cycles per second.

Figure 5.- Oscillograms showing laminar oscillations at various radii.

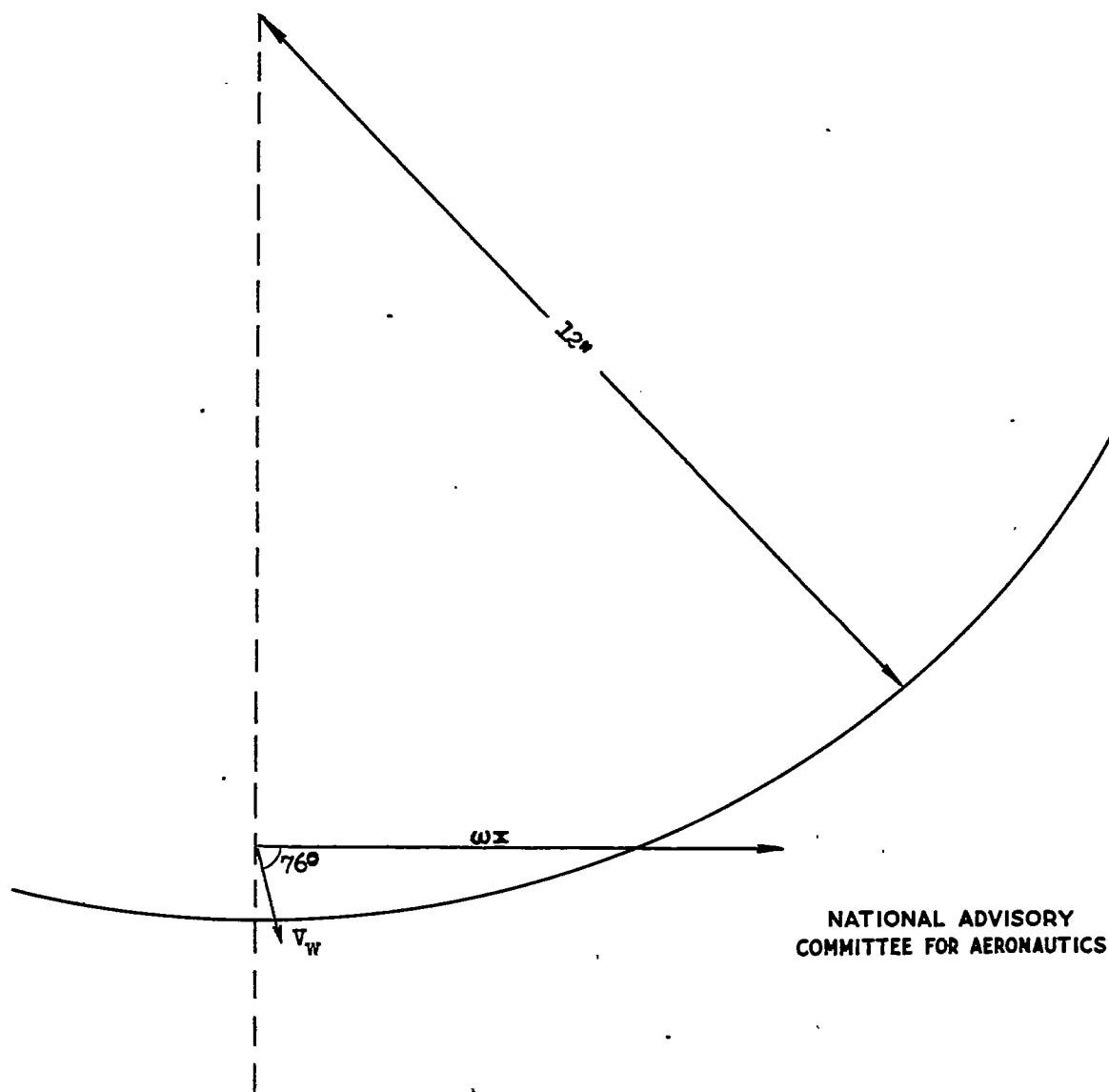


Figure 6.- Direction and comparative magnitude of wave velocity at 11-inch radius on a disk rotating at 500 rpm.